DYNAMIC B-H CURVES OF MAGNETIC MATERIALS UNDER MAGNETIC SWITCHING TRANSIENTS*

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Abstract

The characteristics of a ferrite core saturating inductor under capacitive discharge were investigated both theoretically, with the use of computer modeling techniques on a HP-85 microcomputer, and experimentally on an actual ferrite core inductor.

To correlate the modeling technique with experiment, the voltage across and the current through the ferrite core inductor under capacitive discharge excitation were measured. Since the magnetic flux density and field strength can be determined from these measurements, a dynamic trajectory of the magnetic flux density as a function of the magnetic field strength for the ferrite core was made. The data from this "dynamic B-H curve" was fed into an HP-85 microcomputer and the model generated hysteresis energy and power plots as a function of time. These plots agreed well with the measured data except for a small discontinuity in the theoretical plots due to the piece-wise linear approximation used in modeling.

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I. Introduction

The study of magnetics is often one of sequential sophistication [1,2,3,4].

- o Inductance
  (Reversibly) by Stored Magnetic Energy
  -- linear
  -- saturation nonlinearities
- o Wire losses
  -- from basic circuit theory, $RI^2(t)$
- o Hysteresis loop losses
  -- sinusoidal (e.g., repetitive magnetic switching)

The goal of the work is to calculate

- o Hysteresis loss as a transient
  -- function of time and
  -- to do the design interactively.

The transient hysteresis loss is important for pulsed applications using large volume cores whose economics are dominated by purchase cost because cheaper core materials will inherently have high core losses. Examples under investigation here are the shock transient temperature rise of 145 kV, 80 kA, 2 ms magnetic amplifiers modules and magnetic switch amplifier driven accelerators. The interactive requirement is obvious in studying innovative geometries and materials in small models before scaleup. As an introduction to the more sophisticated and general models [5], the presentation in this paper will use a small magnetic switch [2,6] to obtain transient hysteresis loss.

II. Description of Magnetic Switch

The magnetic switch circuit of Figure II-1 was the end result of a teaching lab in pulse power techniques. At present it switches about 300 V in 100 μs into a 1 kΩ load.

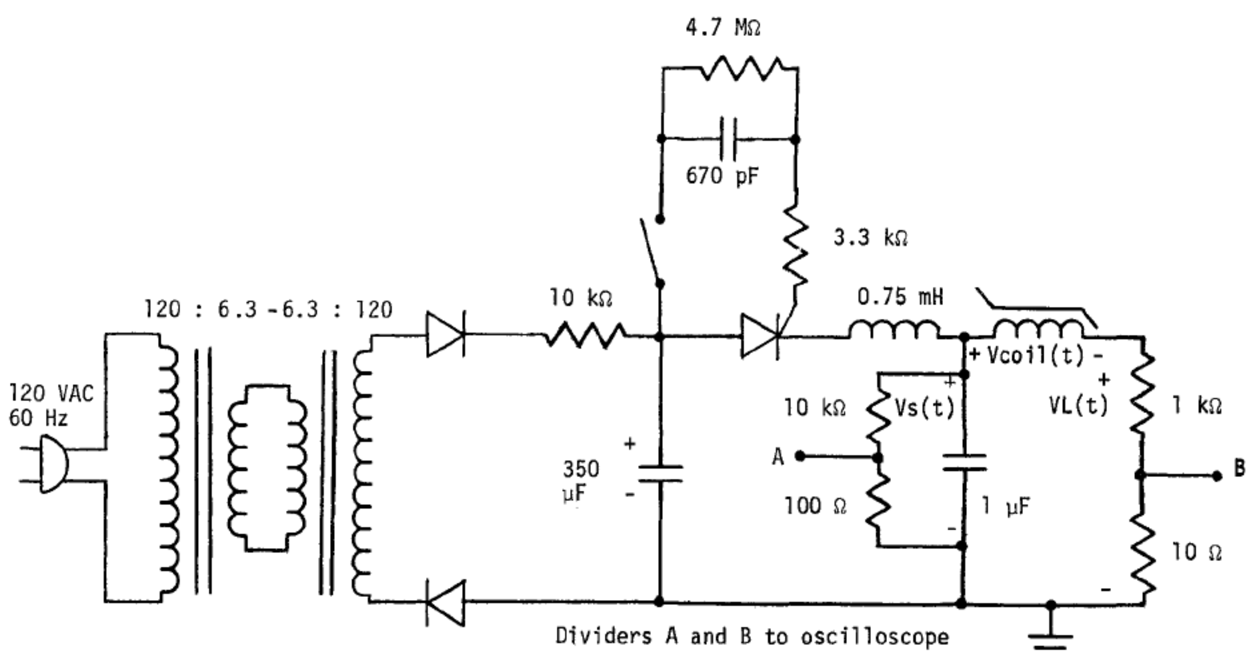

Figure II-1. Magnetic Switch Circuit.

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14. ABSTRACT
The characteristics of a ferrite core saturating inductor under capacitive discharge were investigated both theoretically, with the use of computer modeling techniques on a HP-85 microcomputer, and experimentally on an actual ferrite core inductor. To correlate the modeling technique with experiment, the voltage across and the current through the ferrite core inductor under capacitive discharge excitation were measured. Since the magnetic flux density and field strength can be determined from these measurements, a dynamic trajectory of the magnetic flux density as a function of the magnetic field strength for the ferrite core was made. The data from this "dynamic B-H curve" was fed into an HP-85 microcomputer and the model generated hysteresi.s energy and power plots as a function of time. These p"lots agreed well with the measured data except for a small discontinuity in the theoretical plots due to the piece-wise linear approximation used in modeling.

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The source is a resonantly charged 350 μF capacitor. The unsaturated inductors initially holds off the source voltage until the inductor saturates and magnetically switches the voltage to the load. The sequence is depicted in Figure II-2 by the measured waveforms of the source, Vs(t), magnetic switch, Vms(t), and load voltage, VL(t), as well as load current, IL(t). As shown, Vms is measured differentially from Vs(t) and VL(t) by either analog or digital electronics. All voltages were measured with a digital Nicolet oscilloscope using two-channel, 0.5 μs per point sampling plug-in. For fast, interactive microcomputer calculations and clear drawings only 34 points were used. Straight lines connect the points for easy viewing.

The transformers are for isolation to allow for movement of signal ground and wired back to back (120 : 6.3 V to 6.3 : 120 V) in order to charge the 350 μF electrolytic capacitor to about 195 Vdc. The resonant pulse charging is started by a manually triggered SCR in series with the resonant inductor (a linear, air-core, single-layer solenoid, 0.75 mH, 5 cm diameter, 18 cm long, 297 turns of #28 polythermaleze coated copper wire). In about 70 μs, the source capacitor charges to 380 V for a voltage transfer efficiency of 195%. which is close to the ideal of 200%.

The magnetic switch is made of 304 turns of # 28 polythermaleze coated copper wire wound three fourths of the way around a ferrite toroid. The toroid has inner and outer diameters of 4 and 7 centimeters, respectively and is made of Indiana General type 0-5 material (B_{sat} = 0.47 T, B_r = 0.11 T, μ_r, max = 5,000). The dc wire resistance (Rms) is 5.5 ohm. Future students are to generate a different source of higher voltage in order to obtain progressively shorter switching times in order to define the performance limit of this magnetic switch.

III. Calculational Theory

The two topics of interest are: the dynamic B-H curves and transient hysteresis losses. The theory of each will be discussed separately in this section. The results are given in the next section.

Dynamic B-H Curves

The magnetic field intensity, H(t), is calculated directly from the load current

$$H(t) = 304\ IL(t)/\ 0.17 \qquad \text{(A/m)} \qquad (1)$$

where 304 and 0.17 are the number of turns and geometric mean path length of the magnetic switch core.

The transient magnetic flux density, B(t) is found by

$$B(t) = \int_{start}^{t} 33\ (Vms(t) - R*IL(t))\ dt + Bstart \qquad \text{(J)} \qquad (2)$$

where 33 is the reciprocal of the product of the coil turns and core cross-sectional area and the quantity in parenthesis is the magnetically induced voltage. The Bstart is the initial condition. Starting with virgin material it is zero and becomes offset due to the retentivity after each switching pulse. In time (i.e., after about five switchings) Bstart not only acquires a constant value, but the integral becomes zero after the end of each successive switching pulse.

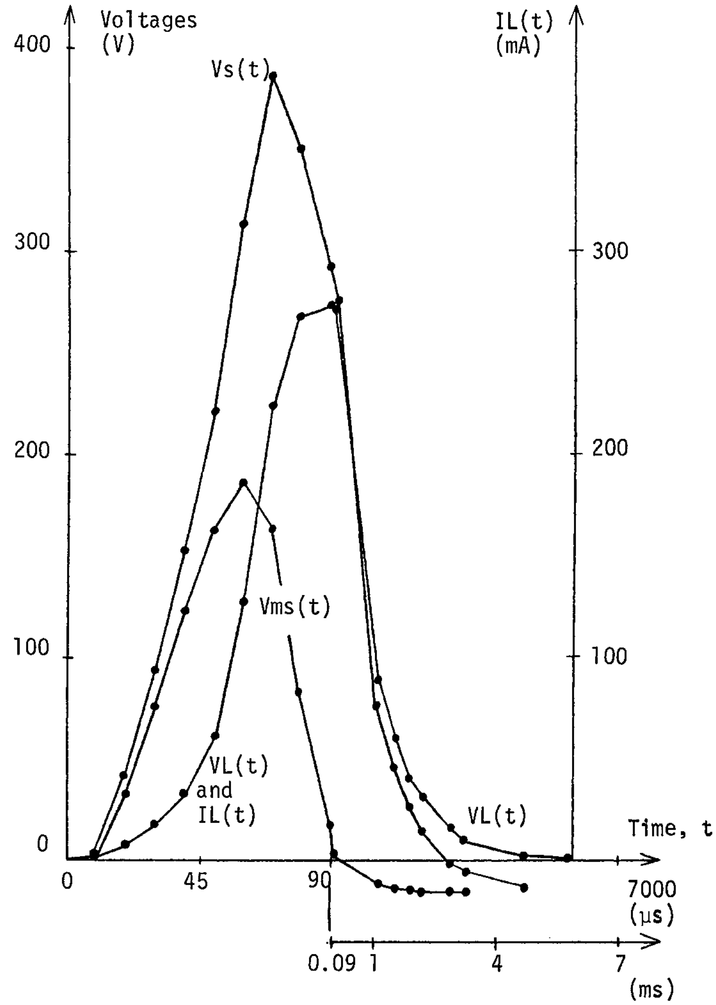


Figure II-2. Source, magnetic switch and load voltages

In practice, it is quite difficult to accurately obtain the constant value of Bstart because of the cumulative error in measuring Vms(t) and IL(t) over several pulses. This error is compounded by the inaccuracies of differential resistive divider measurements. It is further compounded by the dynamic range limit of the recording instrument in measuring hundreds of volts in tens of microseconds while still accurately responding to only volt level signals but lasting several milliseconds. (The large pulse of short duration is evident in Figure II-2 while the small negative pulse of long duration is just visible.) The constant value is believed to be about 0.11 T. If future students need an accurate value it can be obtained by methods such as flux gate [6].

Fortunately only relative values of B(t) are needed during a pulse and only the integral contribution need to be considered. A measure of the relative accuracy for obtaining B(t) would be the value of the integral after each complete switch pulse. The tuning of the dividers and the recording instrument can be checked by comparing the calculated induced voltage, Vms(t) - R*IL(t), with the induced voltage of an unloaded secondary coil (wound on the remaining one-fourth of the toroid.) After tuning the integral comes within 2 mT of zero after each pulse. This represents good performance because it is only 1% of the maximum contribution of the integral which is 263 mT at the peak of each pulse. Only relative values of B(t) will be presented in the results section.

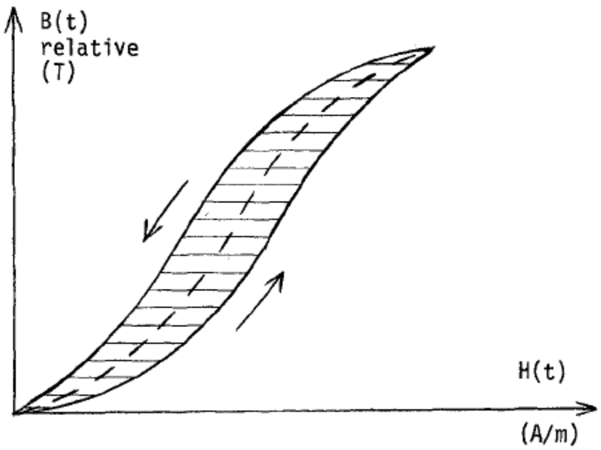
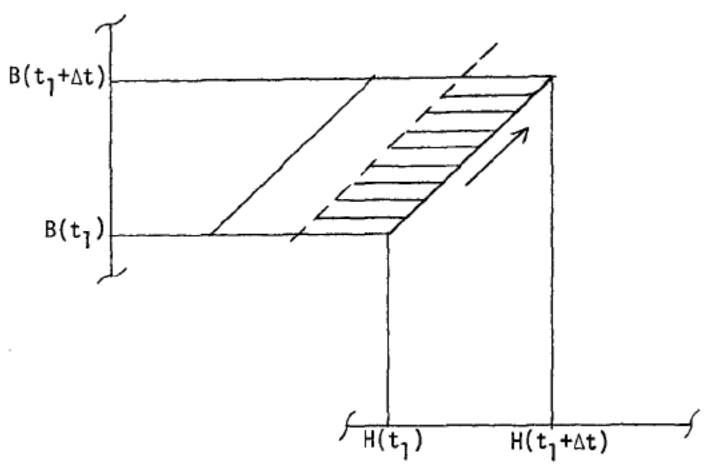
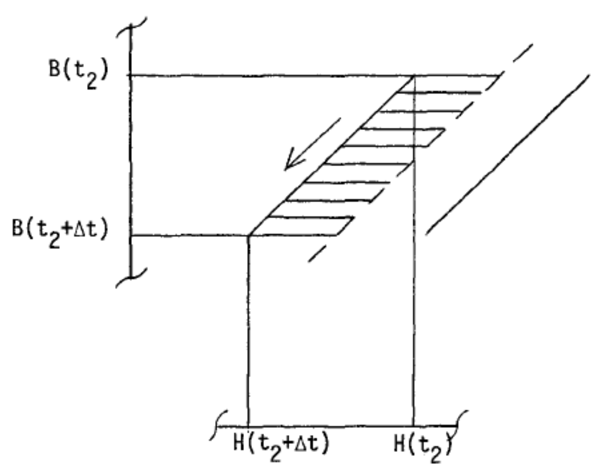


Figure III-1. Cyclic hysteresis loss (shaded area)



a) for increasing B(t), (see arrow)



b) for decreasing B(t) (see arrow)

Figure III-2. Method for calculating transient losses. (shaded area)

Transient Hysterisis Lossed

Historically, the cyclic loss per unit volume is calculated by the closed path integral ($\oint$ HdB) represented by the shaded area in Figure III-1. A first order method for calcuating transient losses will now be discussed using Figures II-1 and -2.

If the paths for increasing and decreasing B(t) are not too dissimiliar, it can be assumed that the hysteresis energy lost on the upward path equals the energy lost on the downward paths. This is shown by the dashed line down the "center" of the hysterisis loop, where the shaded area to the right of the dashed line "equals" the area to the left. On an incremental basis a small horizontal slice through the hysteresis loop of Figure III-1 has been expanded and redrawn in Figure III-2a and for a corresponding upward and downward path, respectively. The center dashed line is numerically chosen so that the shaded areas are the same in parts a and b of the figure. The shaded area is the energy lost to hysteresis over the time period t_1 to $t_1 + \Delta t$ or the period t_2 to $t_2 + \Delta t$. An example of this method is given.

IV. Results

Using the experiment of Section II and the theory of III, the dynamic B-H curves of Figure IV-1 was obtained.

The dots were somewhat randomly selected data points and the circles are linearly interpolated between the data points and are in one-to-one correspondence to data points having the same numerical value of B but on the other path. One very convenient method for offsetting possible selection/interpolation errors (such as the straight dashed line) is to require that losses be always either zero or positively increasing. This scheme is most easily executed when microcomputers automatically execute the desired numerical methods.

The corresponding energy and power lost to hysteresis is given in Figure IV-2 and -3. From these, equivalent circuits models for hysteresis are being obtained.

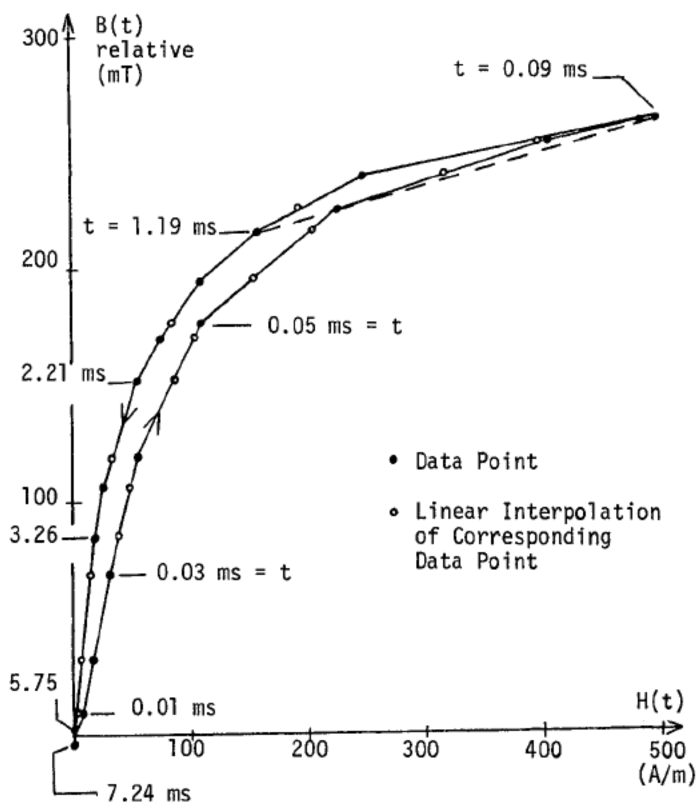


Figure IV-1. Dynamic B-H curves.

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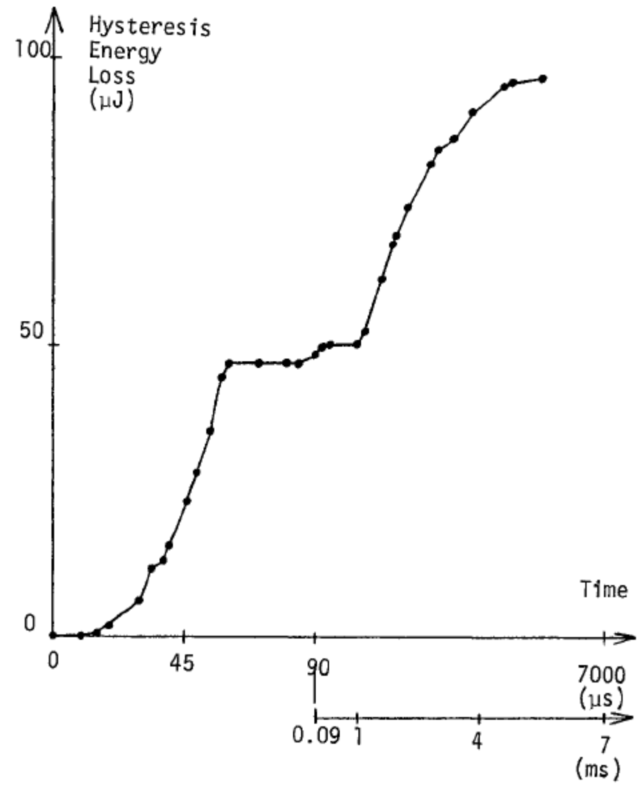

Figure IV-2. Energy lost to hysteresis.

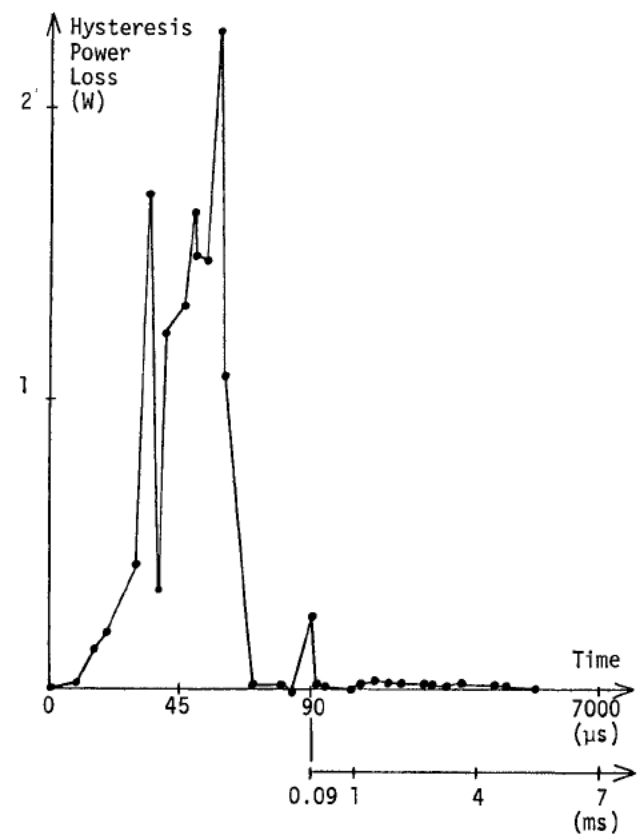

Figure IV-3. Power lost to hysteresis (i.e., the time, integral of Figure V-2).